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jc957 U.S. PTO 11/14/00

Docket No.: 319700031REA

Date: November 14, 2000

Express Mail Label No.: EL 486 598 160 US

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

jc515 U.S. PTO 09/712596 11/14/00

Assistant Commissioner for Patents
Washington, D.C. 20231

REISSUE APPLICATION TRANSMITTAL

Transmitted herewith is the application for reissue of U.S.

[X] Utility Patent [ ] Plant Patent [ ] Design Patent

No. 5,842,154, issued on November 24, 1998.

Inventor(s): Sean Harnett

Title: **FUZZY LOGIC TUNING OF RF MATCHING NETWORK**

Enclosed are the following:

1. ***Specification, Claim(s), And Drawing(s) (37 C.F.R. § 1.173)***

(a) Abstract (page 1), Specification and Claims in double-column format (cols. 1-10) including new Claims 9-37, and Certificate of Correction.

(b) In accordance with 37 C.F.R. Section 1.173(a)(2), please find attached a clean copy of the printed drawings of the patent (5 sheets, Figs. 1-7).

2. ***Declaration And Power Of Attorney***

Three (3) pages of signed Declaration and Power of Attorney.

3. ***Preliminary Amendment***

[ ] Attached

4. ***Letters Patent***

[ ] Original letters patent is attached.

[ ] Declaration that original letters patent lost or inaccessible is attached.

[X] Offer to Surrender by the inventor along with Assent by Assignee for Filing of Reissue Application.

5. ***Petition To Proceed Without Assignee's Assent***

[ ] Attached hereto is a "Petition To Proceed With Reissue Application Without Assignee's Assent".

[ ] The fee payment is authorized in the attached:

[ ] "Reissue Application Transmittal" Form.

[ ] "Completion Of Filing Requirements -- Reissue Application" form.

6. ***Information Disclosure Statement***

[X] Attached

[X] Copies of the IDS citation(s) is/are attached.

7. ***Priority - 35 U.S.C. § 119***

[ ] Priority of application Serial No. __________. Filed on _________, in ____________ is claimed under 35 U.S.C. § 119.

[ ] The certified copy has been filed in prior application Serial No. ________, filed on ____________.

8. ***Basic Filing Fee Calculation (37 C.F.R. § 1.16(h), (I) and (j))***

FILING FEE CALCULATION	Number Claims in Reissue		Number Claims in Patent		Number Extra		Rate		Basic Fee **$710.00**
Total Claims	37	-	8 (20)	=	17	X	$18.00	=	$306.00
Independent Claims	7	-	3	=	4	X	$80.00	=	$320.00
Multiple Dependent Claim(s) Used							$270.00	=	
FILING FEE – NON-SMALL ENTITY									
FILING FEE - SMALL ENTITY: Reduction by 1/2 .... [ ] Verified Statement under 37 C.F.R. §1.27 is enclosed. [ ] Verified Statement filed in prior application.									
Assignment Recordal Fee ($40.00)...									
37 C.F.R. §1.17(k) Fee (non-English application)									
TOTAL									**$1,336.00**

9. ***Small Entity Status***

[ ] A statement that is filing is by a small entity is

[ ] Attached

10. ***Additional Fee Payments***

[ ] Payment is being made for "Petition To Proceed With Reissue Application Without Assignee" (37 C.F.R. § 1.17(h) .... $______

11. ***Total Fees Due***

Filing Fee	$ 710.00
Petition Fee	$ 0.00
Extra Independent Claim	$320.00
Extra Claims	$306.00
Total Fees Due	$1,336.00

12. ***Method Of Payment of Fees***

[X] A check is enclosed to cover the calculated fees. The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 08-0750. A duplicate copy of this document is enclosed.

[ ] The calculated fees will be paid within the time allotted for completion of the filing requirements.

[ ] The calculated fees are to be charged to Deposit Account No. 08-0750. The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to said Deposit Account. A duplicate copy of this document is enclosed.

13. ***Additional Enclosures***

[X] An Assignment of the invention

[ ] is enclosed with a cover sheet pursuant to 37 C.F.R. § 3.11, 3.28 and 3.31.

[X] is of record in a prior application. The assignment is to ENI Technology, Inc., and is recorded at Reel 008815, Frame 0877.

[X] An Establishment of Assignee's Right To Prosecute Application Under 37 C.F.R. § 3.73(b), and Power Of Attorney is enclosed.

[X] An Express Mailing Certificate is enclosed.

[X] Other: Postcard.

Attention is directed to the fact that the correspondence address for this application is:

Harness, Dickey & Pierce, P.L.C.
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(248) 641-1600.

Respectfully,

Date Nov 14, 2000

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Joseph M. Lafata
Reg. No. 37,166

Docket No.: 319700031REA

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Patentee:	ENI Technology, Inc.	**CONSENT BY ASSIGNEE FOR FILING OF REISSUE APPLICATION**
Patent No.:	5,842,154	
Issued:	November 24, 1998	
Serial No.: (reissue)	To Be Assigned	
Filed: (reissue)	To Be Assigned	**EXPRESS MAIL NO. EL 486 598 160 US**
Inventor(s):	Sean Harnett	
Title:	FUZZY LOGIC TUNING OF RF MATCHING NETWORK	

Hon. Commissioner of Patents
And Trademarks
Washington, D.C. 20231

Sir:

This is part of the application for a reissue patent filed herewith based on the original patent identified as follows:

1. The undersigned is an assignee owning

   [x] an undivided interest to the above original patent.
   [ ] a ______% (per cent) interest in the above original patent.

2. The undersigned consents to the accompanying application for reissue.

3. Attached is a "Establishment Of Assignee's Right To Prosecute Application Under 37 C.F.R. § 3.73(b), And Power Of Attorney"

ENI Technology, Inc.

Date: 11-9-00

Robert J. Uelio
Robert J. Uelio
Senior Vice President, Finance & Administration

Docket No.: 319700031REA

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Patentee:	ENI Technology, Inc.	
Patent No.:	5,842,154	**OFFER TO SURRENDER**
Issued:	November 24, 1998	
Serial No.: (reissue)	To Be Assigned	
Filed: (reissue)	To Be Assigned	**EXPRESS MAIL NO. EL 486 598 160 US**
Inventor(s):	Sean Harnett	
Title:	FUZZY LOGIC TUNING OF RF MATCHING NETWORK	

Hon. Commissioner of Patents and Trademarks
Washington, D.C. 20231

Sir:

1. The undersigned applicant of the accompanying reissue application for the reissue of letters patent for the improvement in FUZZY LOGIC TUNING OF RF MATCHING NETWORK, Patent No. 5,842,154 granted to him/her on November 24, 1998, of which

[ ] he/she is now sole owner,

[X] ENI Technology, Inc. is now sole owner by assignment, and on whose behalf and with whose assent the accompanying application is made,

[X] The "Assent By The Assignee" to this reissue application is attached.

Date: 11/10/00

Sean Harnett
Sean Harnett

ASSENT OF ASSIGNEE TO REISSUE

The undersigned, assignee of the entire interest in the above-mentioned letters patent, hereby assents to the accompanying application.

STATEMENT OF ASSIGNEE

[X] Attached is a "Statement Under 37 C.F.R. 3.73(b)," establishing the right of the assignee to take action in this reissue.

ENI Technology, Inc.

Date: 11-9-00

Robert J. Lelio

Robert J. Lelio
Senior Vice President, Finance & Administration

HARNESS, DICKEY & PIERCE, P.L.C.
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Hon. Commissioner of Patents
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Washington, D.C. 20231

Sir:

EXPRESS MAILING CERTIFICATE

Applicant:	Sean Harnett
Serial No. (if any):	To Be Assigned
For:	FUZZY LOGIC TUNING OF RF MATCHING NETWORK
Docket:	3197-000031/REA
Attorney:	MPB/JML

"Express Mail" Mailing Label Number............................. EL 486 598 160 US

Date of Deposit .... November 14, 2000

I hereby certify and verify that the accompanying **Express Mailing Certificate; Check in the amount of $1,336 ($710-reissue filing fee, $306-claims in excess of 20 (17@$18), and $320-additional independent claims (4@$80)); Reissue Application Transmittal (in duplicate) 15-page application including Abstract, Certificate of Correction, and new claims 9-37; Five (5) Sheets of Drawings (Figs. 1-7); executed Reissue Application Declaration and Power of Attorney; executed Offer To Surrender; executed Consent By Assignee For Filing of Reissue Application; executed Establishment of Assignee's Right to Prosecute Application and Power of Attorney; Information Disclosure Statement; Form PTO-1449; nine (9) U.S. references and two (2) miscellaneous documents and return postcard** are being deposited with the United States Postal Service "Express Mail Post Office To Addressee" service under 37 C.F.R. 1.10 on the date indicated above and are addressed to the Commissioner of Patents and Trademarks, Washington, D.C. 20231.

Annette D'Alessandro

Annette D'Alessandro

FUZZY LOGIC TUNING OF RF MATCHING NETWORK

BACKGROUND OF THE INVENTION

This invention relates to plasma generation equipment, and is particularly directed to an automatic RF matching network to match the impedance of a reactive plasma chamber or similar non-linear load to a constant impedance (e.g., 50 ohms) output of an RF generator or similar RF source. The invention is more particularly concerned with a fuzzy logic technique that is capable of controlling two, or more, tunable elements in the matching network using both the phase error signal and magnitude error signal associated with the matching network.

In a typical RF plasma generator arrangement, a high power RF source produces an RF wave at a preset frequency, i.e., 13.56 MHZ, and this is furnished along a power conduit to a plasma chamber. The RF power is also typically provided at a fixed, known impedance, e.g., 50 ohms. Because there is typically a severe impedance mismatch between the RF power source and the plasma chamber, an impedance matching network is interposed between the two. There are non-linearities in the plasma chamber which make it difficult to simply set the impedance match network at fixed positions for a plasma process. At the input to the matching network there is located a phase and magnitude error detector that produces two (or more) error signals representing the magnitude of impedance error and phase error. Magnitude error is the difference between the magnitude of the nominal input impedance (typically 50Ω and the magnitude of the actual input impedance. Phase error is the deviation between the phase at the nominal input impedance (typically zero degrees) and the phase at the actual input impedance. The error signals also indicate the direction or sign (+ or −) of the magnitude error and phase error.

The conventional matching network uses these two error signals to control two variable tuning elements: phase error being used to control one tuning element and magnitude error being used to control the other tuning element. The phase and magnitude error signals drive motors associated with variable capacitors or perhaps a tuning slug of a variable inductor. The error signals drop to a low or zero level when a matched condition has been achieved.

The conventional system has experienced difficulty in quickly achieving matched impedance under a number of conditions. One primary problem is that the current design does not address the fact that each tuning element affects both error signals. Because of this effect, the error signals may drive one or both of the tuning elements away from the match or tune point. This prolongs the tuning process, and causes slower, less reliable tuning. Another problem arises because the phase and magnitude error signals alone do not always provide enough information to drive the matching network to the tune point. This means that the matching network may have "lost conditions" where it will be unable to reach impedance match. A third problem is that the error signal produced by a given movement of a tuning element varies with the tuning element's position. In other words, if the tuning element is near the minimum end of its travel, a 10% change in position may produce a 50% change in error signal amplitude, but if the tuning element is near the maximum end of its travel, the same 10% change might produce only a 5% change in error signal amplitude. This will cause the control loop stability to vary depending upon the position of the tuning elements. However, at the present time, no practical system even tracks the tuning element (e.g., rotor) position as an input.

A cross-point approach to address the first-mentioned problem has been proposed previously, but still uses only a single error signal for each of two tuning elements. Another problem is that this approach requires a hard, fixed threshold rather than a gradual transition.

A lost-recovery approach has been proposed to address the second problem mentioned above, namely the "lost conditions" problem. In this approach the system detects that impedance match has been lost, and then moves the tuning elements to predetermined "lost recovery" positions, from which it can tune to a match. This approach wastes considerable time in recovering impedance match, and may not work with every load in the tuning range.

The industry does not seem to have recognized the third problem arising from the non-linearity of the error signal across its range. Also, the desirability of using more than one error signal to control each tuning element has not been recognized, nor has any process been proposed for combining multiple error signals to control each of the tuning elements associated with the impedance matching network.

Fuzzy logic has been employed as a control algorithm in many applications, and has the advantage of reducing a complex multi-dimensional treatment to a rather straightforward algorithm based on a simple set of rules. Fuzzy logic is based on Fuzzy Set Theory, a branch of mathematics developed by Prof. Lotfi A. Zadeh in the 1960's. Fuzzy logic provides a robust, non-linear and efficient approach to control by mapping inputs to outputs using a minimal amount of code. The basis for fuzzy logic and fuzzy controls has been explained in many places in the mathematical and engineering literature. Basically, the fuzzy logic control process can be described as a small number steps or stages. First, the process control engineer establishes a number of overlapping fuzzy sets, e.g., "high positive," "medium positive," "zero" or small, "medium negative," and "high negative." In the first stage, i.e., "fuzzification," crisp, discrete input values are fuzzified, that is, they are converted into appropriate degrees of membership in overlapping fuzzy sets. Then, in a rule application stage, rules are applied to define the relation between the input variables and the output variables. These rules are provided in terms of a "fuzzy inference function" and represent a relation that should be intuitive to the process engineer. These can be a series of IF-AND-THEN statements, or can be constructed as a straightforward table, grid or matrix. An output or defuzzification stage converts the fuzzy variables to crisp output values that are applied as control values or signals to a control device, such as the rotor of a variable capacitor.

No one has previously considered employing fuzzy logic to the control the tuning of an impedance match network, and no one has previously appreciated that an application of fuzzy logic would resolve the three problems mentioned above.

OBJECTS AND SUMMARY OF THE INVENTION

It is an object of this invention to provide a scheme for controlling the tuning of an RF matching network that avoids the drawbacks of the prior art.

It is another object of this invention to provide automatic tuning of an RF matching network that avoids problems of single variable control of the tuning elements, "lost conditions" and non-linearity across the tuning range.

It is a further object to provide automatic tuning of the RF matching network which is fast and reliable, and which is easily implemented and adjusted.

According to an aspect of this invention, a fuzzy logic method is employed for tuning an RF matching network of the type having an input at which is applied RF power at a given frequency and at a given impedance, and an output which applies such power to an RF load having a non-constant impedance, such as an RF plasma chamber. The matching network has a phase-magnitude error detector providing a phase error signal and a magnitude error signal related respectively to the differences between nominal and actual input phase angle, i.e., $\Delta\phi$ and between nominal and actual impedance ΔZ. The matching network has at least a first variable impedance having a driven element for varying its impedance, and a second variable impedance having a driven element for varying its impedance. The fuzzy logic control technique involves the steps of supplying the phase and the magnitude error signals to a fuzzy logic controller, wherein each error signal has a magnitude and direction. Then the error signals are each applied to a fuzzy logic inference function based on membership in one or more fuzzy sets, which may be overlapping fuzzy sets. The value, i.e., the size and direction of each error signal enjoys membership in one, two, or more overlapping fuzzy sets. Fuzzy logic rules are applied to the phase and magnitude error signals according to the fuzzy sets for which said first and second error signals enjoy membership. A plurality of drive signal values are obtained, based on the fuzzy logic rules for each of the phase and magnitude error signals. The drive signal values are weighted according to respective fuzzy inference functions for which the error signals enjoy membership. Then the weighted drive signal values are combined to produce an output drive signal for the first variable impedance device driven element. A similar process creates an output drive signal for the second variable impedance. According to the fuzzy logic rules, the phase and magnitude error signals are used jointly to obtain each of the output drive signals.

The fuzzy logic rules can be expressed as a matrix of N×M drive current values, where N is the number of fuzzy sets of said first error signal and M is the number of fuzzy sets of said second error signal. Here, to obtain each drive current value, there is a given set of rules applying the first error signal and the second error signal.

A fuzzy logic controller is provided according to another aspect of this invention for tuning an RF matching network, wherein the matching network is positioned between a source of applied RF power at a given frequency and at a given impedance, and an RF load, such as an RF plasma chamber, having a non-constant impedance. A phase-magnitude error detector produces a phase error signal and a magnitude error signal related respectively to the phase error and magnitude error in input impedance, as discussed earlier. The matching network also has at least a first variable impedance having a driven element for varying the impedance thereof and a second variable impedance having a driven element for varying the impedance thereof. The fuzzy logic controller has input means to receive the values of the phase and magnitude error signals. The controller applies these values of error signals to a fuzzy logic inference function based on a number of overlapping fuzzy sets. The values of error signals enjoy membership in one, two, or more overlapping fuzzy sets. Fuzzy logic rules are applied to the phase and magnitude error signals, with the rules depending on the fuzzy sets for which the error signals enjoy membership. Drive signal values are obtained according to the fuzzy logic rules for each fuzzy set for which the error signals enjoy membership. The drive signal values are weighted according to the respective fuzzy inference functions for the values of these error signals. Then the weighted drive signal values are combined to produce an output drive signal for the first variable impedance device driven element. Additional drive signal values are obtained based on additional fuzzy logic rules for each of the phase and magnitude error signals. Then these additional drive signal values are weighted according to additional respective fuzzy inference functions, and the weighted drive signal values are combined to produce an output drive signal for the second variable impedance device driven element.

The fuzzy logic controller quickly drives the tuning elements to a matched impedance state, and avoids lost condition problems. The fuzzy logic controller can be implemented in hardware, or can be based on a programmed device such as a digital signal processor (DSP) or a microprocessor. The fuzzy logic controller function can operate in background, or can employ a separate hardware device to free the DSP for other functions such as signal processing, motor control, user interface, or other functions. A separate independent PC can be employed to carry out the fuzzy logic tuning.

Further enhancements in performance can be obtained by employing additional inputs. For example, tuning element positions can be used as inputs to linearize loop gain as a function of position. This can achieve higher overall loop gain and faster tuning speeds. A reduction or elimination of lost conditions can be achieved by using additional sensors, e.g., voltage and current at the RF plasma chamber, and then applying the detected levels as additional inputs to the fuzzy logic controller.

The improvements of this invention use fuzzy logic to provide a practical method to analyze multiple inputs and to produce signals which will drive multiple tuning elements. In a minimal system, the fuzzy controller inputs can consist of phase and magnitude errors, and the fuzzy outputs can consist of one or both of the drive signals for the tuning elements.

The invention can be easily extended to control of three or more variable tuning devices.

The above and many other objects, features, and advantages of this invention will become apparent from the ensuing description of a preferred embodiment, which is to be read in conjunction with the accompanying Drawing.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a system block diagram of an RF plasma process incorporating an impedance match net with a fuzzy logic control system according to one embodiment of this invention.

FIG. 2 is an enlarged schematic diagram of the match net and control system of this embodiment.

FIGS. 3 and 4 are charts of the fuzzy logic inference functions or membership functions with respect to the fuzzy sets of impedance magnitude error and phase angle error, respectively.

FIGS. 5A and 5B are fuzzy logic rule application matrices for first and second variable impedance tuning drive signals according to an embodiment of this invention.

FIGS. 6A and 6B are fuzzy logic rule application matrices for first and second variable impedance tuning drive signals according to another embodiment of this invention.

FIG. 7 illustrates a three-dimensional fuzzy logic rule application matrix that can be employed with additional embodiments of this invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference to the Drawing figures, and initially to FIG. 1, an RF plasma processing system 10 is shown for

purposes of example. A plasma generator **12** provides RF electrical power at a predetermined frequency, i.e., 13.56 MHz. The output of the generator **12** is followed by a harmonic/subharmonic filter **14**, which is then followed by an impedance matching network **16**, which supplies the electrical power through a voltage/current sensor system **18** to an input of a plasma chamber **20**. The matching unit **22**, with a phase/magnitude sensor impedance matching unit **22**, with a phase/magnitude sensor **24** connected at its input. The sensor provides a phase error signal $\Delta\phi$ that is proportional to the difference between the nominal input impedance phase angle and the actual phase angle ($\phi-\phi_O$) of the impedance matching unit, and also provides a magnitude error signal ΔZ that is proportional to the difference between the nominal input impedance and actual input impedance ($Z-Z_O$)

A fuzzy logic controller **26** has inputs to receive the phase error signal $\Delta\phi$ and to receive the magnitude error signal ΔZ, and respective control signal outputs CS1 and CS2 for controlling respective first and second variable impedance devices within the unit **22**. An optional third control signal output CS3 is shown in ghost lines. Additional sensors **28** can optionally provide the fuzzy logic controller **26** with additional input signals, e.g., time rate of change of phase error. The fuzzy logic controller can be a separate unit, but may also be incorporated into the housing of the impedance matching network **16**. The operating codes, including the fuzzy logic rule matrix and fuzzy logic inference function algorithm can be stored in a memory device (not shown) of the controller **26**. This memory device can be a programmable read-only memory, such as an E-PROM, capable of storing downloaded program codes, and providing for revision of the codes to optimize the tuning of the matching network **16**. It is also possible to employ a "fixed match" arrangement, and use the error signals $\Delta\phi$ and ΔZ to control the frequency of the plasma generator **12**.

FIG. **2** shows details of the match net unit **22** and the fuzzy logic controller **26** from which for the operation of this invention can be explained. The match net unit **22** includes a number of variable impedance devices for effecting tuning to establish an impedance match between the 50 ohms of the RF generator **12** and the unknown impedance of the RF plasma chamber **20**. Besides the fixed impedances (not shown) there can be a first tuning capacitor C1 and a second capacitor C2. Optionally, there can also be a third tuning capacitor C3 and/or a tunable inductor L. The first and second tuning capacitors each have a tuning element motor **M1** and **M2**, respectively. If additional tuning elements are desired, a third tuning element motor **M3** can be provided for the third capacitor C3. Also, a motor (not shown) can be provided for the tuning slug of the tunable inductor L.

The fuzzy logic controller **26** here accomplishes three operations on the input signals, which are here shown as the phase error signal $\Delta\phi$, the impedance magnitude error signal ΔZ, and any additional error signals, e.g., from other sensors **28**. The error signals are first applied to a fuzzification stage **29**, where the error signals are applied to respective fuzzy inference functions **30**, **32**, **34**. These functions here are shown as sequences of overlapping triangular or trapezoidal ramp functions, and will be explained in detail shortly. Then, in a rule evaluation stage **35**, predetermined rules are applied, depending on the fuzzy sets in the fuzzification stage **29** to which each of the error signals enjoys membership. These can be expressed as IF-AND-THEN logic statements, such as IF the phase error is negative and large, AND IF the magnitude error is positive and medium, THEN apply a positive large drive signal as CS1 and apply a negative medium drive signal as CS2. The rules for all combinations of fuzzy set memberships of phase error and magnitude error can be considered as a matrix of N×M rules, where N is the number of fuzzy sets of phase error and M is the number of fuzzy sets of magnitude error. The several drive signal values obtained in the rule evaluation stage **35** are then converted to discrete drive signal values CS1, CS2, CS3, etc., in a defuzzification stage **37**.

In the fuzzification stage **29**, ramp-shaped membership functions, or fuzzy inference functions **32** and **30** are employed, as shown in FIGS. **3** and **4**, respectively for the impedance magnitude error ΔZ, and for the phase error $\Delta\phi$. These are overlapping functions, as shown, so that the respective error signal values are partly members of one fuzzy set and also partly members of an overlapping fuzzy set. In the example shown here in FIG. **3**, the magnitude error ΔZ is of a positive value, and has a membership of 35% of zero error, and 65% positive medium error. At the same time, as shown in FIG. **4**, the phase error $\Delta\phi$ has a negative value, and enjoys a 25% membership in the zero error fuzzy set and a 75% membership in the negative medium fuzzy set. These membership values are used for weighting and combining the respective drive signal values that are obtained according to the fuzzy rules application stage **35**.

In the defuzzification stage **37**, a weighting factor is applied to the drive signal values that are obtained, based on the conditions of magnitude error positive medium, phase error negative medium; magnitude error positive medium, phase error zero; magnitude error zero, phase error negative medium; and magnitude error zero, phase error zero (for the example in FIGS. **3** and **4**). These are weighted according to their respective membership values, and are combined for each drive signal CS1, CS2, CS3, etc. This results in bringing each of the tuning devices quickly to a tuned condition, and accounts for the effect of each device on the phase error and magnitude error signals. The amount of movement for each tuning device also depends on the size and sign (positive or negative) of the phase and magnitude error. Thus, this system avoids the major pitfalls of prior art impedance match networks, as mentioned previously.

FIGS. **5A** and **5B** are matrices of typical fuzzy logic rules for a given impedance match network. Here, the notation used in the grid squares indicates the size and direction of motor current to be applied to the first tuning capacitor (FIG. **5A**) and to be applied to the second tuning capacitor (FIG. **5B**). These are PL—positive large; PM—positive medium; Ze—zero; NM—negative medium; and NL—negative large. The labels on the vertical and horizontal axes represent the fuzzy sets for the magnitude error and phase error, namely NL—negative large; NM—negative medium; Ze—zero; PM—positive medium; and PL—positive large. As is apparent, these matrices are somewhat asymmetric or unbalanced, as they have to account for the problems of non-linearity, cross-over, and lost conditions, as mentioned before. These matrices can be arrived at rather quickly by the process engineer, starting with orthogonal or symmetric matrices, where the drive current values depend on only one error signal. A pair of orthogonal matrices are shown in FIGS. **6A** and **6B**. Based on the engineer's experience and by making intuitive adjustments to the matrix, in particular at the conditions where cross-over and lost conditions may be likely to occur, the process engineer can try modified rule sets against a synthetic load. By obtaining the results of the tuning algorithm the matrices can be changed incrementally, as need be, for each iteration. Within a reasonable number of trials, the process engineer will arrive at an optimal pair of rule set matrices, like those of FIGS. **5A** and **5B**.

The fuzzy logic tuning process of this invention achieves a good impedance match rapidly, without undue hunting and without encountering the problems noted above.

It is also possible to employ rule sets of three, or more, variables to control the impedance match net in a more complex environment. For example, FIG. 7 illustrates a possible rules matrix showing error signal variables along its three axes, namely, magnitude error, phase error, and time rate of change of phase error. Of course, there are many other possibilities, and the number of input variables is not limited to only three. To account for the differences in error signal that vary with tuning element position, the rotor positions of the tuning capacitors C1, C2, and C3 can be included as inputs to the fuzzy logic controller. Also, rather than overlapping fuzzy sets, as shown here, it is possible that at least some of the fuzzy sets not overlap, or that the variables enjoy membership in three or more fuzzy sets.

While the invention has been described above in respect to an embodiment of the invention, it should be understood that the invention is not limited to that precise embodiment. Rather, many modifications and variations will present themselves to persons skilled in the art without departure from the scope and spirit of the invention, which is defined in the appended claims.

I claim:

1. Fuzzy logic method of tuning an RF matching network of the type having an input at which is applied RF power at a given frequency and at a given impedance, and an output which applies said power to an RF load having a non-constant impedance, said matching network including a phase-magnitude error detector means providing a phase error signal and a magnitude error signal related respectively to impedance phase angle error and impedance magnitude error, and said matching network comprising at least a first variable impedance having a driven element for varying the impedance thereof and a second variable impedance having a driven element for varying the impedance thereof; the method comprising:

supplying said phase and said magnitude error signals to a fuzzy logic controller, wherein each said error signal has a magnitude and direction,

applying each said error signal to a fuzzy logic inference function based on a number of overlapping fuzzy sets, and where the value of error signal enjoys membership in one or more fuzzy sets;

applying fuzzy logic rules to said phase and magnitude error signals according to the fuzzy sets for which said first and second error signals enjoy membership;

obtaining drive signal values based on said fuzzy logic rules for each of said phase and magnitude error signals;

weighting said drive signal values according to the respective fuzzy inference functions for which said error signals enjoy membership; and

combining said weighted drive signal values to produce an output drive signal for said first variable impedance device driven element.

2. Fuzzy logic method of tuning an RF matching network according to claim 1, further comprising

obtaining drive signal values based on additional fuzzy logic rules for each of said first and second error signals;

weighting said drive signal values according to additional respective fuzzy inference functions; and

combining such weighted drive signal values to produce an output drive signal for said second variable impedance device driven element.

3. Fuzzy logic method of tuning an RF matching network according to claim 2, wherein said fuzzy logic rules comprise a matrix of N×M drive signal values, where N is the number of fuzzy sets of said first error signal and M is the number of fuzzy sets of said second error signal, and each drive signal value corresponds to a given set of said first error signal and a given set of said second error signal.

4. Fuzzy logic method of tuning an RF matching network according to claim 1, said fuzzy sets being centered respectively about zero, a medium positive value, a medium negative value, a high positive value, and a high negative value.

5. A fuzzy logic controller for tuning an RF matching network, wherein said matching network is positioned between a source of applied RF power at a given frequency and at a given impedance, and an RF load having a non-constant impedance, said matching network including a phase-magnitude error detector means providing a phase error signal and a magnitude error signal related respectively to impedance phase angle error and impedance magnitude error, and said matching network comprising at least a first variable impedance having a driven element for varying the impedance thereof and a second variable impedance having a driven element for varying the impedance thereof; the fuzzy logic controller comprising input means receiving values of said phase and magnitude error signals; means for applying the values of said error signals to a fuzzy logic inference function based on a number of overlapping fuzzy sets, and where the values of error signals enjoy membership in one or more fuzzy sets; means for applying fuzzy logic rules to said phase and magnitude error signals according to the fuzzy sets for which said error signals enjoy membership; means for obtaining drive signal values according to said fuzzy logic rules for each set for which said error signals enjoy membership; means for weighting said drive signal values according to the respective fuzzy inference functions for the values of said error signals; and means for combining said weighted drive signal values to produce an output drive signal for said first variable impedance device driven element.

6. Fuzzy logic controller according to claim 5, further comprising means for obtaining additional drive signal values based on additional fuzzy logic rules for each of said phase and magnitude error signals; means for weighting said additional drive signal values according to additional respective fuzzy inference functions; and means for combining such weighted drive signal values to produce an output drive signal for said second variable impedance device driven element.

7. Fuzzy logic method of tuning a tunable RF device of the type having an input at which is applied RF power at a given frequency and at a given impedance, and an output, including an error detector means providing a first error signal and a second error signal, and said tunable RF means including at least a first variable impedance having a driven element for varying the impedance thereof and a second variable impedance having a driven element for varying the impedance thereof; the method comprising:

supplying said first and said second error signals to a fuzzy logic controller, wherein each said error signal has a magnitude and direction,

applying each said error signal to a fuzzy logic inference function based on a number of overlapping fuzzy sets, and generating a membership value that corresponds to the amount of overlapping membership of the error signal value in one or more fuzzy sets;

applying fuzzy logic rules to said first and second error signals according to the fuzzy sets for which said first and second error signals enjoy *membership;*

obtaining a plurality of drive signal values based on said fuzzy logic rules for each of said first and second error signals;

weighting said drive signal values according to the respective membership values for said error signals; and

combining said weighted drive signal values to produce an output drive signal for said first variable impedance device driven element.

8. Fuzzy logic method of tuning a tunable RF device according to claim **7**, further comprising

obtaining a plurality of additional drive signal values based on additional fuzzy logic rules for each of said first and second error signals;

weighting said additional drive signal values according to additional respective fuzzy inference functions; and

combining such weighted additional drive signal values to produce an output drive signal for said second variable impedance device driven element.

√9. An electrical network comprising:

a radio frequency (RF) generator for generating an RF signal, the RF generator having a source impedance;

a load receiving the RF signal, the RF signal providing a driving energy to the load, the load having a variable load impedance;

a matching network interposed between the RF generator and the load, the matching network having a network impedance which may be varied, the matching network detecting at least one of a phase and magnitude error and generating at least one of a corresponding phase error signal and a magnitude error signal, the matching network varying at least one of the phase and the magnitude in order to vary the network impedance; and

a controller receiving the at least one phase error signal and magnitude error signal, the controller applying fuzzy logic to the at least one of the phase error signal and the magnitude error signal in order to generate at least one control signal to vary the network impedance, thereby matching the source impedance and the load impedance.

10. The network of claim 9 wherein the controller further comprises a fuzzy inference module receiving the at least one phase and magnitude error signals and defining a membership value that varies in accordance with membership in at least one of a fuzzy set.

11. <u>The network of claim 10 wherein the controller further comprises a rules module having a set of rules applied in accordance with the membership values, the rules module generating at least one fuzzy output.</u>

12. <u>The network of claim 11 wherein the controller further comprises a defuzzification module, the defuzzification module converting the at least one fuzzy output to the at least one control signal.</u>

13. <u>The network of claim 9 wherein the matching network further comprises at least one of a variable capacitance and a variable inductance.</u>

14. <u>The network of claim 9 wherein the matching network further comprises a circuit for varying the network impedance.</u>

15. <u>The network of claim 9 wherein the load is a RF plasma chamber.</u>

16. <u>An electrical network comprising:</u>

<u>a radio frequency (RF) generator for generating an RF signal, the RF generator having a source impedance,</u>

<u>a load receiving the RF signal, the RF signal providing a driving energy to the load, the load having a variable load impedance;</u>

<u>a matching network interposed between the RF generator and the load, the matching network having a network impedance which may be varied, the matching network detecting at least one network parameter and generating at least one sensed signal, the matching network varying the network impedance in order to match the load impedance and the source impedance; and</u>

<u>a controller receiving the at least one sensed signal, the controller applying fuzzy logic to the at least one sensed signal in order to generate at least one control signal to vary the network impedance, thereby matching the source impedance and the load impedance.</u>

17. <u>The network of claim 16 wherein the controller further comprises a fuzzy inference module receiving the at least one sensed signal and defining a membership value that varies in accordance with membership in at least one of a fuzzy set.</u>

18. <u>The network of claim 17 wherein the controller further comprises a rules module having a set of rules applied in accordance with the membership values, the rules module generating at least one fuzzy output.</u>

19. The network of claim 18 wherein the controller further comprises a defuzzification module, the defuzzification module converting the at least one fuzzy output to the at least one control signal.

20. The network of claim 16 wherein the matching network includes at least one of a variable capacitance and a variable inductance.

21. The network of claim 16 wherein the matching network further comprises a circuit for varying the network inductance.

22. The network of claim 16 wherein the matching network further comprise a circuit for varying the network impedance.

23. The network of claim 9 wherein the load is a RF plasma chamber.

24. A method of tuning an RF impedance matching network having an input which receives RF power and an output which applies the power to a RF load, the matching network having a variable impedance, comprising the steps of:

determining a phase error and a magnitude error and generating a corresponding phase error signal and a corresponding magnitude error signal; and

applying fuzzy logic to the phase and magnitude error signals to generate fuzzy output signals based upon the phase and the magnitude error signals and generating a control signal to adjust the variable impedance of the matching network.

25. The method of claim 24 wherein the step of applying fuzzy logic further comprises applying the phase and magnitude error signals to a fuzzy logic inference function, the phase and magnitude error signals each having at least one respective membership value in at least one fuzzy set.

26. The method of claim 25 wherein the step of applying fuzzy logic further comprises applying logic rules to the at least one respective membership value to generate at least one respective fuzzy output value.

27. The method of claim 26 wherein the step of applying logic rules further comprises the step of weighting the at least one respective fuzzy output value according to the at least one respective membership value.

28. The method of claim 27 wherein the step of applying fuzzy logic rules further comprises the step of combining said weighted at least one respective fuzzy output value to produce the control signal.

29. The method of claim 26, wherein the fuzzy logic rules comprise a matrix of NxM fuzzy output values, where N is the number of fuzzy sets of a first sensed signal and M is the number of fuzzy sets of a second sensed signal, and each fuzzy output value corresponds to a predetermined set of the first sensed signal and a predetermined set of the second sensed signal.

30. The method of claim 25 wherein the at least one fuzzy set comprises a plurality of fuzzy sets centered respectively about zero, a medium positive value, a medium negative value, a high positive value, and a high negative value.

31. A method of tuning an RF impedance matching network having an input which receives RF power and an output which applies the power to a RF load, the matching network having a variable impedance, comprising the steps of:

determining a network parameter and generating a corresponding sensed signal that varies in accordance with the network parameter; and

applying fuzzy logic to the sensed signal to generate fuzzy output signals based upon the sensed signal and generating a control signal to adjust the variable impedance of the matching network.

32. The method of claim 31 wherein the step of applying fuzzy logic further comprises applying the sensed signal to a fuzzy logic inference function, the sensed signal having at least one respective membership value in at least one fuzzy set.

33. The method of claim 32 wherein the step of applying fuzzy logic further comprises applying logic rules to the at least one respective membership value to generate at least one respective fuzzy output value.

34. The method of claim 33 wherein the step of applying logic rules further comprises the step of weighting the at least one respective fuzzy output value according to the at least one respective membership value.

35. The method of claim 34 wherein the step of applying fuzzy logic rules further comprises the step of combining said weighted at least one respective fuzzy output value to produce the control signal.

36. The method of claim 33, wherein the fuzzy logic rules comprise a matrix of NxM fuzzy output values, where N is the number of fuzzy sets of the sensed signal and M is the number of fuzzy sets of a second sensed signal, and each fuzzy output value corresponds to a predetermined set of the first sensed signal and a predetermined set of the second sensed signal.

37. The method of claim 32 wherein the at least one fuzzy set comprises a plurality of fuzzy sets centered respectively about zero, a medium positive value, a medium negative value, a high positive value, and a high negative value.

ABSTRACT

A fuzzy logic control arrangement is provided for an impedance match network of the type that is typically employed between a source of RF power at a given impedance, e.g., 50 ohms, and a non-linear load whose impedance can vary in magnitude and phase, e.g., an RF plasma. The fuzzy logic controller fuzzifies the phase and the magnitude error signals. The error signals are applied to a fuzzy logic inference function based on a number of fuzzy sets. The values of the error signals enjoy some degree of membership in one or more fuzzy sets. Fuzzy logic rules are applied to the phase and magnitude error signals. In a defuzzification stage, drive signal values are obtained for moving the tuning elements of the variable impedances. The drive signal values are weighted according to respective fuzzy inference functions for which the error signals enjoy membership. Then the weighted drive signal values are combined to produce output drive signals.

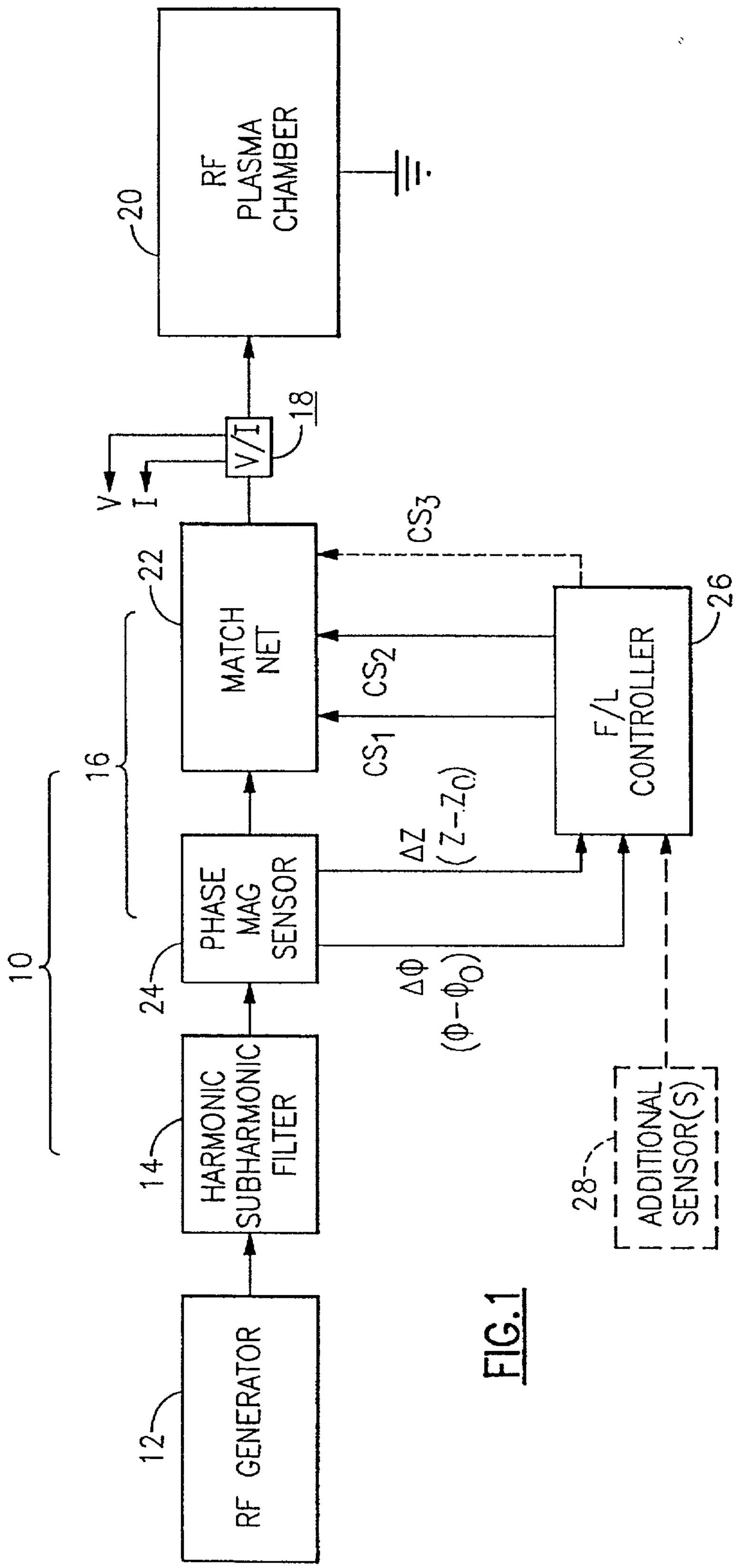
RF PLASMA CHAMBER
20
V/I
18
V
I
MATCH NET
22
CS3
CS2
CS1
F/L CONTROLLER
26
16
10
PHASE MAG SENSOR
24
ΔZ (Z-Z0)
ΔΦ (Φ-Φ0)
HARMONIC SUBHARMONIC FILTER
14
ADDITIONAL SENSOR(S)
28
RF GENERATOR
12

FIG.1

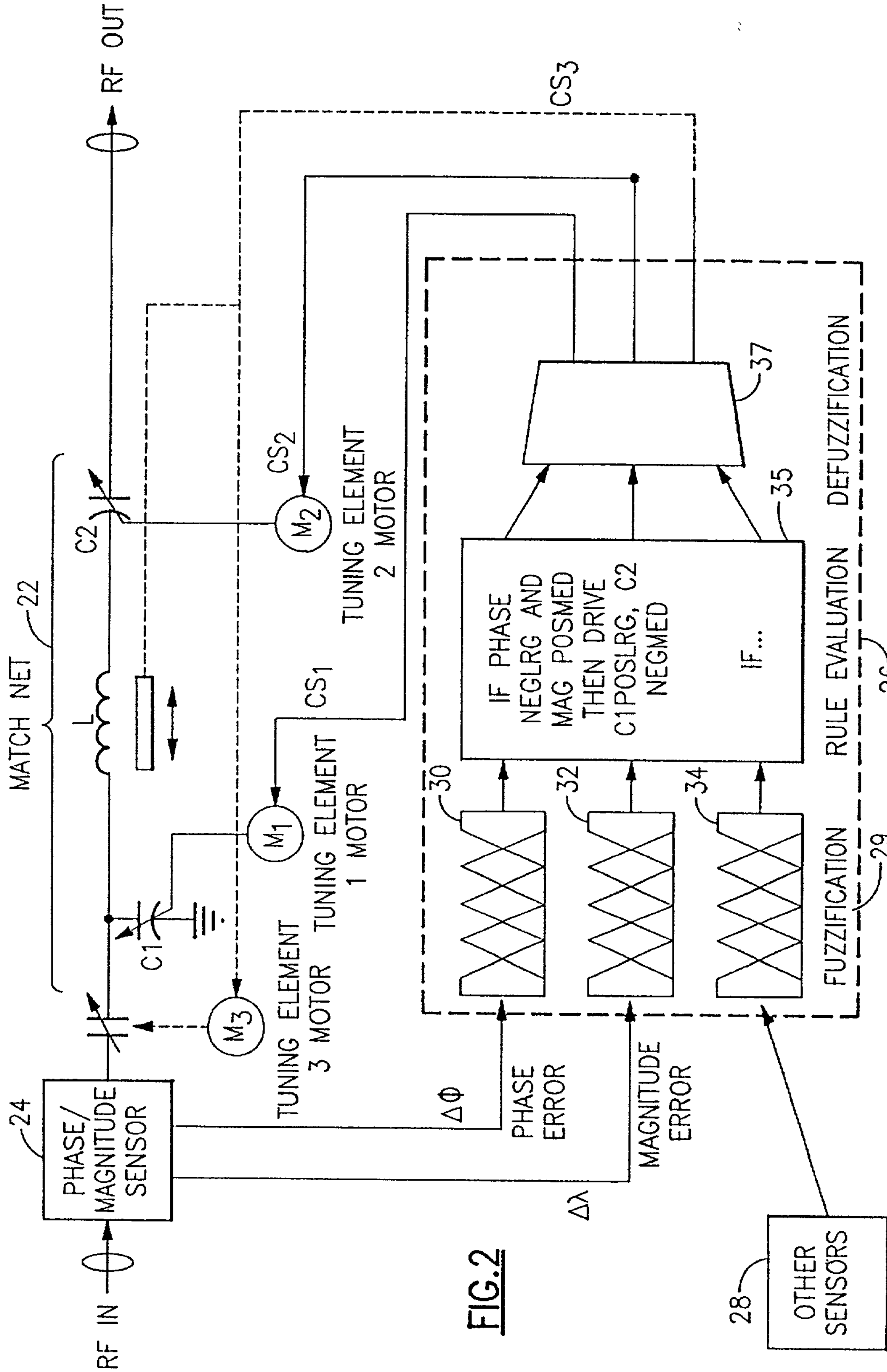
RF IN
RF OUT
PHASE/ MAGNITUDE SENSOR
24
MATCH NET
22
L
C1
C2
M_1
M_2
M_3
TUNING ELEMENT 1 MOTOR
TUNING ELEMENT 2 MOTOR
TUNING ELEMENT 3 MOTOR
CS_1
CS_2
CS_3
$\Delta\Phi$
PHASE ERROR
$\Delta\lambda$
MAGNITUDE ERROR
OTHER SENSORS
28
30
32
34
FUZZIFICATION
29
IF PHASE NEGLRG AND MAG POSMED THEN DRIVE C1POSLRG, C2 NEGMED
IF...
35
RULE EVALUATION
26
37
DEFUZZIFICATION

FIG.2

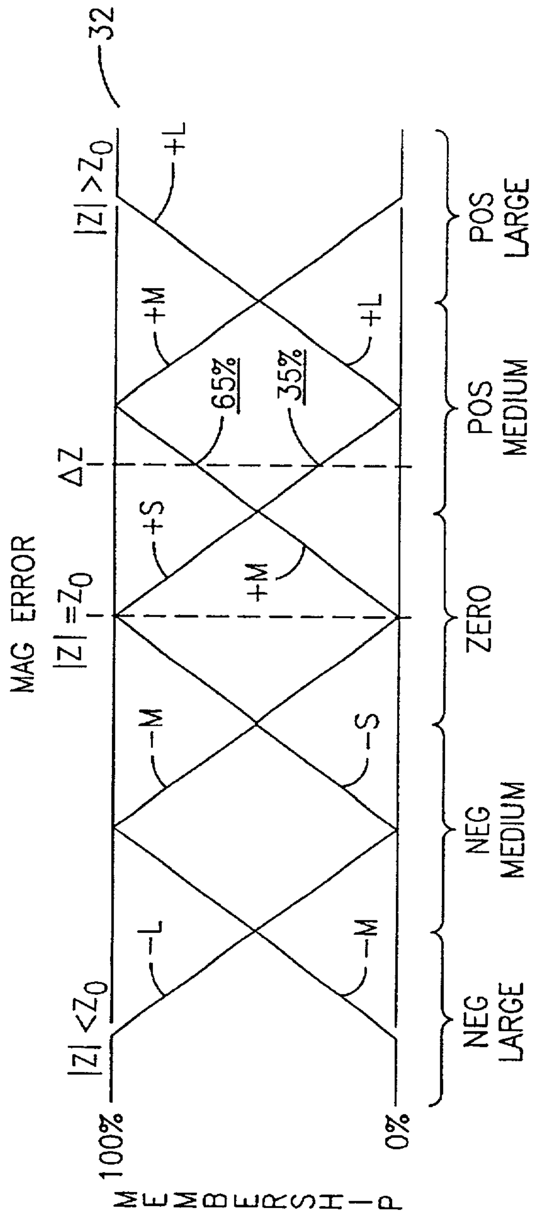
32
MAG ERROR
|Z| <Z0
|Z| =Z0
ΔZ
|Z| >Z0
-L
-M
-S
+S
+M
+L
65%
35%
100%
0%
MEMBERSHIP
NEG LARGE
NEG MEDIUM
ZERO
POS MEDIUM
POS LARGE

FIG.3

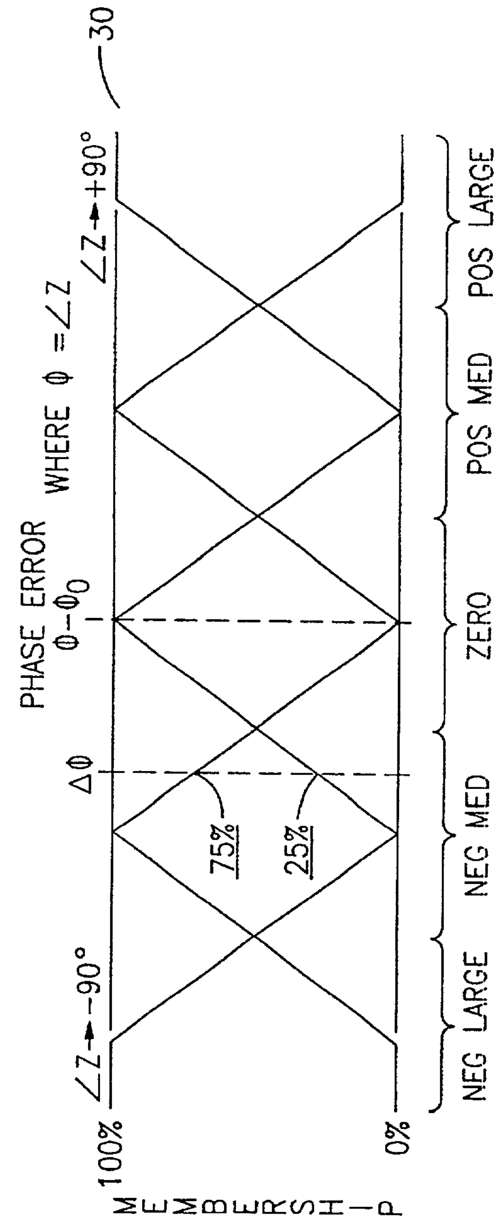
30
PHASE ERROR
Φ−Φ0
WHERE Φ =∠Z
∠Z→−90°
ΔΦ
∠Z→+90°
75%
25%
100%
0%
MEMBERSHIP
NEG LARGE
NEG MED
ZERO
POS MED
POS LARGE

FIG.4

SC1 CURRENT

MAGNITUDE \ PHASE	NL	NM	Ze	PM	PL
NL	PL	Ze	NM	NM	NL
NM	PL	Ze	NM	NL	NL
Ze	PL	PM	Ze	NM	NM
PM	PL	PM	PM	Ze	NM
PL	PL	PL	PM	Ze	NL

FIG.5A

SC2 CURRENT

MAGNITUDE \ PHASE	NL	NM	Ze	PM	PL
NL	PL	PL	PL	Ze	NL
NM	PL	PM	PM	Ze	NL
Ze	PM	Ze	Ze	NM	NL
PM	Ze	NM	NM	NM	NL
PL	NL	NL	NL	NL	NL

FIG.5B

SC1 CURRENT

MAGNITUDE \ PHASE	NL	NM	Ze	PM	PL
NL	PL	PM	Ze	NM	NL
NM	PL	PM	Ze	NM	NL
Ze	PL	PM	Ze	NM	NL
PM	PL	PM	Ze	NM	NL
PL	PL	PM	Ze	NM	NL

FIG.6A

SC2 CURRENT

MAGNITUDE \ PHASE	NL	NM	Ze	PM	PL
NL	PL	PL	PL	PL	PL
NM	PM	PM	PM	PM	PM
Ze	Ze	Ze	Ze	Ze	Ze
PM	NM	NM	NM	NM	NM
PL	NL	NL	NL	NL	NL

FIG.6B

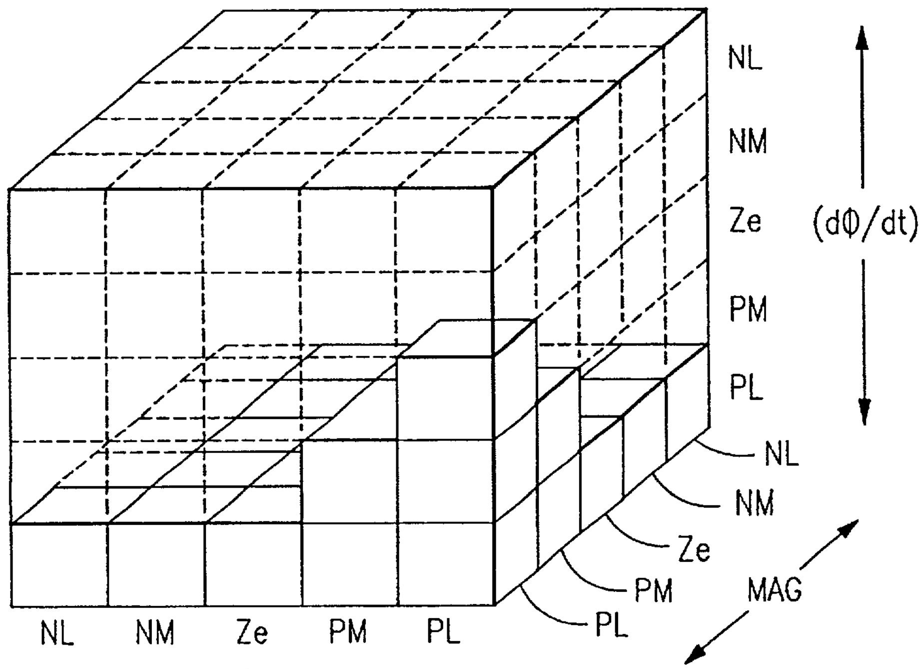

FIG.7

Practitioner's Docket No. 319700031REA **PATENT**

REISSUE APPLICATION DECLARATION AND POWER OF ATTORNEY (BY INVENTOR(S) OR ASSIGNEE)

DECLARATION BY THE INVENTOR(S)

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name, I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter that is described and claimed in letters patent number 5,842,154, granted on November 24, 1998, and for which invention I solicit a reissue patent on the invention entitled FUZZY LOGIC TUNING OF RF MATCHING NETWORK the specification of which

[X] is attached hereto.

[ ] was filed on ______________, as reissue application number / and was amended on __________________ (if applicable).

[ ] I hereby declare that there is no assignee for this application.

ACKNOWLEDGEMENT OF REVIEW OF PAPERS AND DUTY OF CANDOR
(37 C.F.R. § 1.175)

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information that is material to patentability as defined in Title 37, Code of Federal Regulations, § 1.56.

PRIORITY CLAIM

I hereby claim foreign priority benefits under Title 35, United States Code, section 119(a)-(d) of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

PRIOR FOREIGN APPLICATION(S)

			Priority Claim	
(Number)	(Country)	(Day/Month/Year filed)	Yes	No
(Number)	(Country)	(Day/Month/Year filed)	Yes	No
(Number)	(Country)	(Day/Month/Year filed)	Yes	No

I hereby claim the benefit under Title 35, United States Code, 119(e) of any United States Provisional application(s) listed below:

PRIOR PROVISIONAL APPLICATIONS

(application serial number)	(Month / Day / Year filed)
(application serial number)	(Month / Day / Year filed)

STATEMENT OF INOPERATIVENESS
OR INVALIDITY OF ORIGINAL PATENT
(37 C.F.R. § 1.175)

That I believe the original patent to be

[X] partly

[ ] wholly

inoperative or invalid by reason of (37 C.F.R. § 1.175(a)(1)):

[ ] a defective specification

[ ] a defective drawing

[X] the patentee claiming more or less than the patentee had a right to claim in the patent. More particularly, I claimed less literally than I had a right to claim in the patent; namely, by limiting all of the claims of the patent to the recitation of elements unnecessary to define the invention in a literal reading of its broadest aspects (although no believed to be so limiting under the doctrine of equivalents and other legal principals) and primarily by reason of the specific wording of all of the claims so as to specifically recite that the error signals are phase and magnitude error signals.

That the error(s) listed above and all other errors, which are being corrected, up to the time of the filing of this reissue declaration, arose without any deceptive intention on the part of the applicant. (37 C.F.R. § 1.175(a)(2)).

[ ] Corroborating affidavits or declarations of others accompany this declaration.

DECLARATION AND POWER OF ATTORNEY

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

I hereby appoint Michael P. Brennan, Reg. No. 30,612 and Joseph M. Lafata, Reg. No. 37,166, and each principal, attorney of counsel, associate and employee of Harness, Dickey & Pierce, P.L.C., who is a registered Patent Attorney, my attorney with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith. I request the Patent and Trademark Office to direct all correspondence and telephone calls relative to this application to Harness, Dickey & Pierce, P.L.C., P.O. Box 828, Bloomfield Hills, Michigan 48303 (248) 641-1600.

Full name of sole or first inventor Sean Harnett

Inventor's Signature: Sean Harnett

Date: 11/10/00

Residence: 50 Brooktree Drive, Penfield, New York 14526

Citizenship: United States of America

Post Office Address: 50 Brooktree Drive, Penfield, New York 14526

Docket No. 319700031REA

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Patentee:	ENI Technology, Inc.	**ESTABLISHMENT OF ASSIGNEE'S RIGHT TO PROSECUTE APPLICATION UNDER 37 C.F.R. § 3.73(b), AND POWER OF ATTORNEY**
Patent No.:	5,842,154	
Issued:	November 24, 1998	
Serial No.: (reissue)	To Be Assigned	
Filed: (reissue)	To Be Assigned	**EXPRESS MAIL NO. EL 486 598 160 US**
Inventor(s):	Sean Harnett	
Title:	FUZZY LOGIC TUNING OF RF MATCHING NETWORK	

Hon. Commissioner Of Patents & Trademarks
Washington, D. C. 20231

Sir:

Under 37 C.F.R. § 3.73(b), the undersigned hereby establishes the below-named Assignee's ownership in the above-identified Application:

Assignee: ENI Technology, Inc.
100 Highpower Road
Rochester, New York 14623-3498

The documentary evidence of a chain of title from the original owner to the Assignee is provided in the Assignment Document(s):

___ filed herewith.

_X_ previously filed,

Reel No. 8815, Frame No. 0877.

I hereby declare that all statements made herein of my own knowledge are true, and that all statements made on information and belief are believed to be true; and further that these statements are made with the knowledge that willful false statements, and the like so made, are punishable by fine or imprisonment, or both, under Section 1001, Title 18 of the

United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

Assignee furthermore hereby appoints Michael P. Brennan, Reg. No. 30,612, Joseph M. Lafata, Reg. No. 37,166, as attorney of record, with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith. I request the Patent and Trademark Office to direct all correspondence and telephone calls relative to this application to Michael P. Brennan, Harness, Dickey & Pierce, P.L.C. P.O. Box 828, Bloomfield Hills, Michigan 48098 (248) 641-1600. The undersigned (whose title is supplied below) is empowered to sign this certificate on behalf of the assignee.

Robert J. Lelio
Name: Robert J. Lelio
Title: Senior Vice President, Finance & Administration
Assignee: ENI Technology, Inc.

Date: 11-9-00